Strings and Particle Physics

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Questions

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- Can we incorporate particle physics models within the framework of string theory?

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- Can we incorporate particle physics models within the framework of string theory?

Recent progress:

- explicit model building towards the MSSM
  - Heterotic brane world
  - local grand unification
- moduli stabilization and Susy breakdown
  - warped throats
  - modulus or mirage mediation

The road to the Standard Model

What do we want?

- gauge group $SU(3) \times SU(2) \times U(1)$
- 3 families of quarks and leptons
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But there might be more:

- supersymmetry (SM extended to MSSM)
- neutrino masses (see-saw mechanism)

as a hint for a large mass scale around 10^{16} GeV

Grand Unification

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- unified multiplets (e.g. spinors of SO(10))
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But there remain a few difficulties:

- breakdown of GUT group (large representations)
- doublet-triplet splitting problem (incomplete multiplets)
- proton stability (need for R-parity)

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In fact string theory gives us a variant of GUTs

- complete multiplets for fermion families
- split multiplets for gauge- and Higgs-bosons
- partial Yukawa unification

in a geometrical set-up known as local GUTs, realized in the framework of the “heterotic braneworld”.

(Förste, HPN, Vaudrevange, Wingerter, 2004)

Localization

Quarks, Leptons and Higgs fields can be localized:

- in the Bulk ($d = 10$ untwisted sector)
- on 3-Branes ($d = 4$ twisted sector fixed points)
- on 5-Branes ($d = 6$ twisted sector fixed tori)

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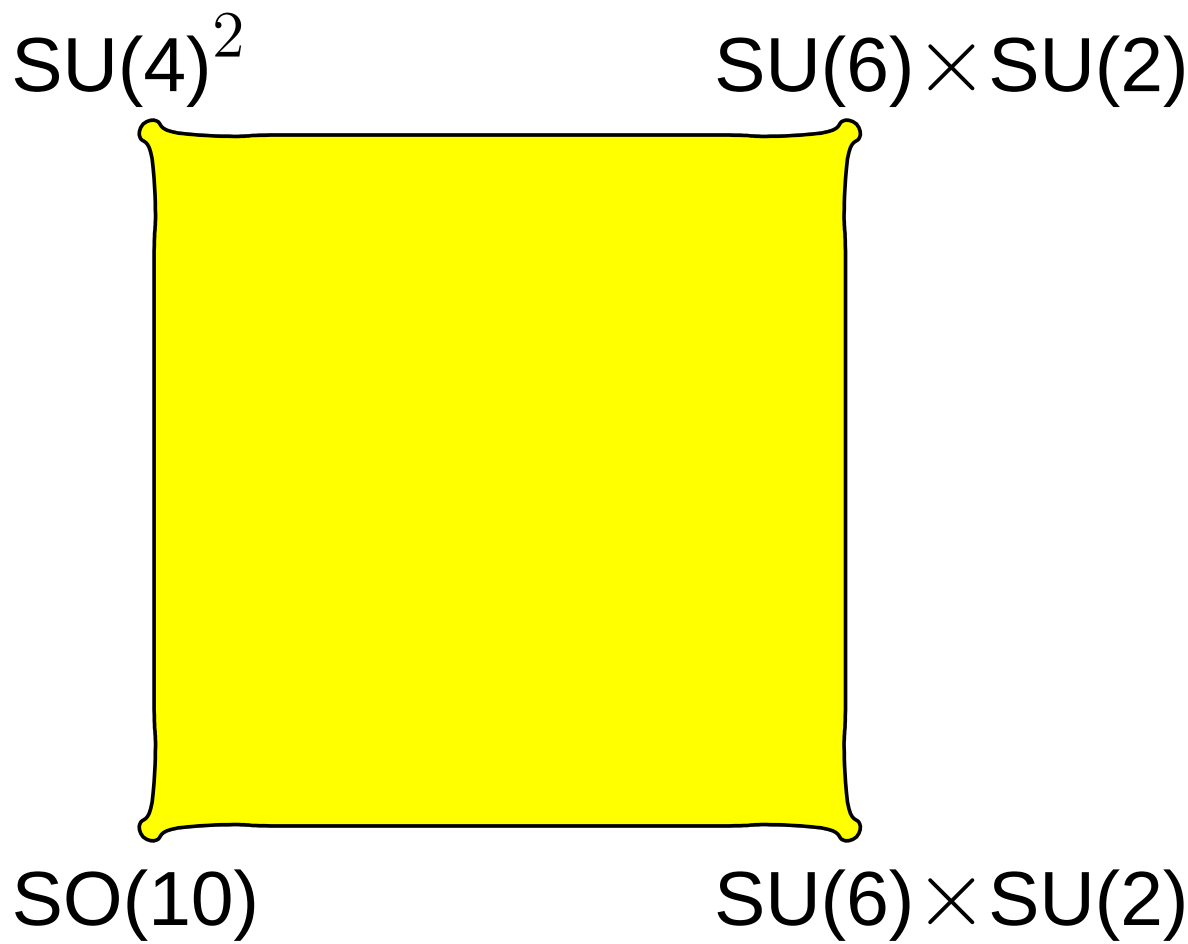
but there is also a “localization” of gauge fields

- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

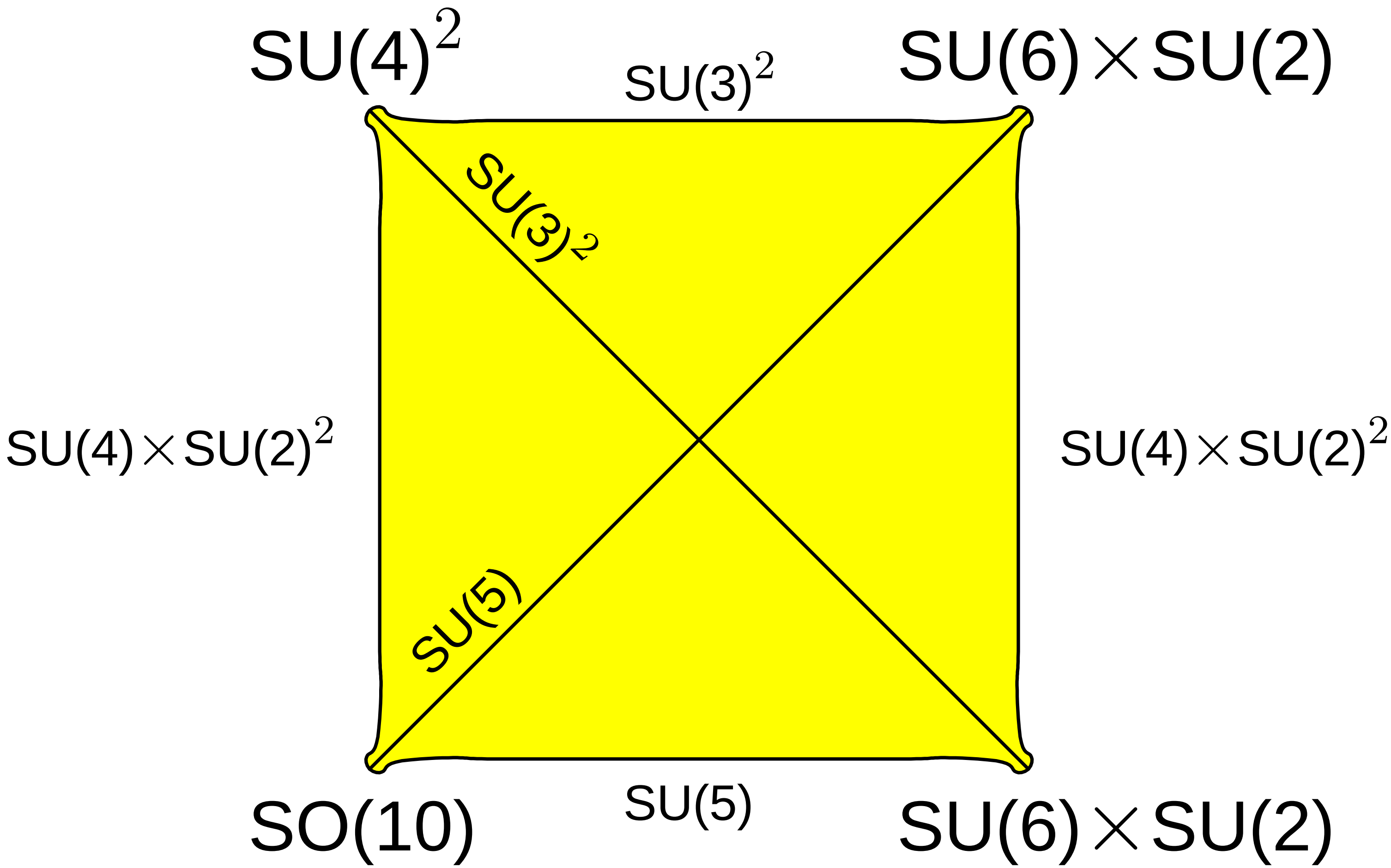
Observed 4-dimensional gauge group is common subroup of the various localized gauge groups!

Localized Gauge Symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



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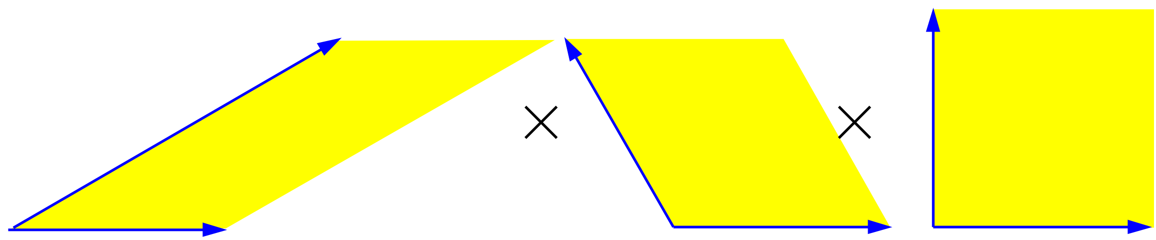
Still there could be remnants of $SO(10)$ symmetry

- 16 of SO(10) at some branes
- correct hypercharge normalization
- R-parity

that are very useful for realistic model building ...

Benchmark Scenario: Z_6 II orbifold



(Kobayashi, Raby, Zhang, 2004; Buchmüller, Hamaguchi, Lebedev, Ratz, 2004)

- provides fixed points and fixed tori
- allows $SO(10)$ gauge group
- allows for localized 16-plets for 2 families
- $SO(10)$ broken via Wilson lines
- nontrivial hidden sector gauge group

Selection Strategy

criterion	$V^{\mathrm{SO}(10),1}$	$V^{\mathrm{SO}(10),2}$
② models with 2 Wilson lines	$22,000$	$7,800$
③ SM gauge group $\subset$ SO(10)	3563	1163
④ 3 net families	1170	492
⑤ gauge coupling unification	528	234
⑥ no chiral exotics	128	90

(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006)

The road to the MSSM

The benchmark scenario leads to

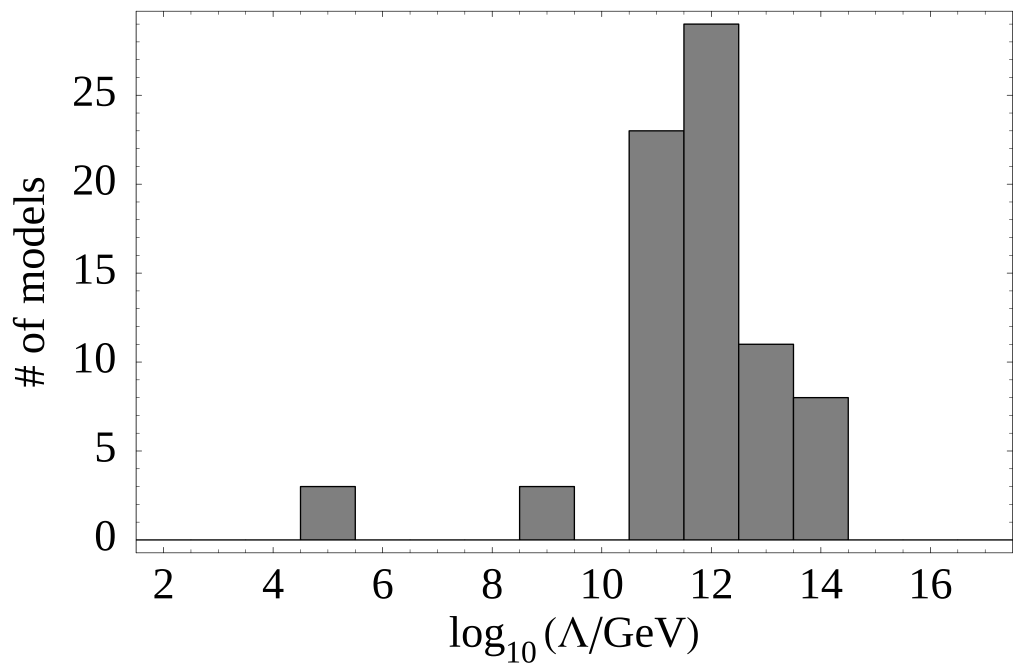
- 200 models with the exact spectrum of the MSSM (absence of chiral exotics)
- local grand unification (by construction)
- gauge- and (partial) Yukawa unification

  (Raby, Wingerter, 2007)
- examples of neutrino see-saw mechanism

  (Buchmüller, Hamguchi, Lebedev, Ramos-Sanchez, Ratz, 2007)
- models with R-parity + solution to the μ-problem

  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)
- hidden sector gaugino condensation

Hidden Sector Susy Breakdown



$m_{3/2} = \Lambda^3/M^2_{\text{Planck}}$ (with $\Lambda = \mu \exp(-1/g^2_{\text{hidden}}(\mu))$)
from hidden sector gaugino condensation

(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006)

Two Basic Questions

- origin of the small scale?
- stabilization of moduli?

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Recent progress in

- moduli stabilization via fluxes in warped compactifications of Type IIB string theory

  (Dasgupta, Rajesh, Sethi, 1999; Giddings, Kachru, Polchinski, 2001)

- generalized flux compactifications of heterotic string theory

  (Becker, Becker, Dasgupta, Prokushkin, 2003; Gurrieri, Lukas, Micu, 2004)

- combined with gaugino condensates and “uplifting”

  (Kachru, Kallosh, Linde, Trivedi, 2003)

Fluxes and gaugino condensation

Is there a general pattern of the soft mass terms?

We have (from warped flux and gaugino condensate)

$$W = \text{something} - \exp(-X)$$

where "something" is small and X is moderately large.

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$$W = \text{something} - \exp(-X)$$

where "something" is small and X is moderately large.

In fact in this simple scheme

$$X \sim \log(M_{\text{Planck}}/m_{3/2})$$

providing a "little" hierarchy.

(Choi, Falkowski, HPN, Olechowski, Pokorski, 2004)

Mixed Modulus Anomaly Mediation

The contribution from "Modulus Mediation" is therefore suppressed by the factor

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Numerically this factor is given by: $X \sim 4\pi^2$.

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Thus the contribution due to "Anomaly Mediation" (suppressed by a loop factor) becomes competitive, leading to a Mixed Modulus-Anomaly-Mediation scheme.

For reasons that will be explained later we call this scheme

MIRAGE MEDIATION

(Loaiza, Martin, HPN, Ratz, 2005)

The little hierarchy

$$m_X \sim \langle X \rangle m_{3/2} \sim \langle X \rangle^2 m_{\text{soft}}$$

is a generic signal of such a scheme

- moduli and gravitino are heavy
- gaugino mass spectrum is compressed

(Choi, Falkowski, HPN, Olechowski, 2005; Endo, Yamaguchi, Yoshioka, 2005; Choi, Jeong, Okumura, 2005)

- such a situation occurs if SUSY breaking is "sequestered" on a warped throat

(Kachru, McAllister, Sundrum, 2007)

Mirage Unification

Mirage Mediation provides a

- characteristic pattern of soft breaking terms.

(Choi, Jeong, Okumura, 2005)

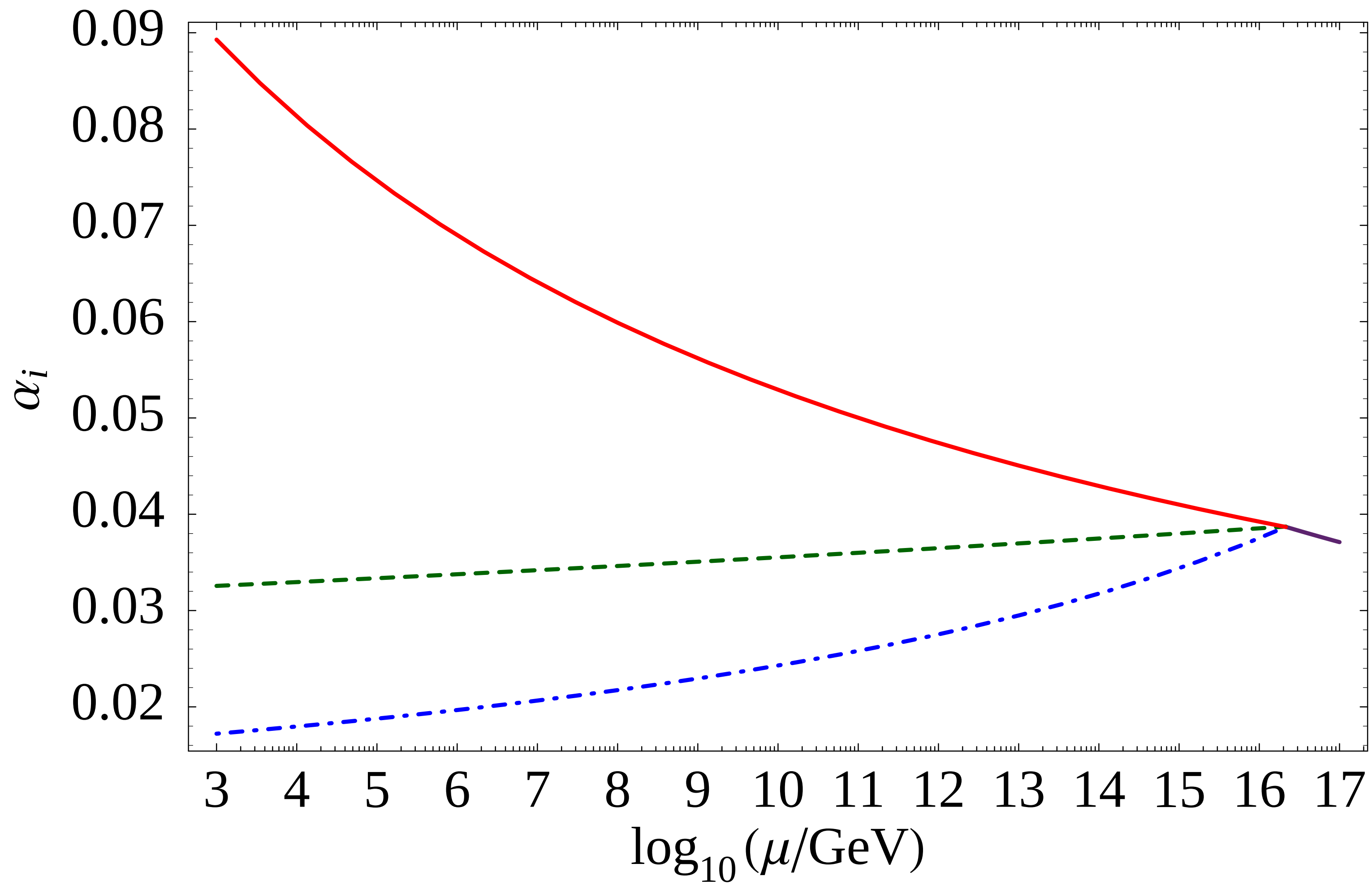
Gaugino masses receive two contributions

$$M_{1/2} = M_{\text{modulus}} + M_{\text{anomaly}}$$

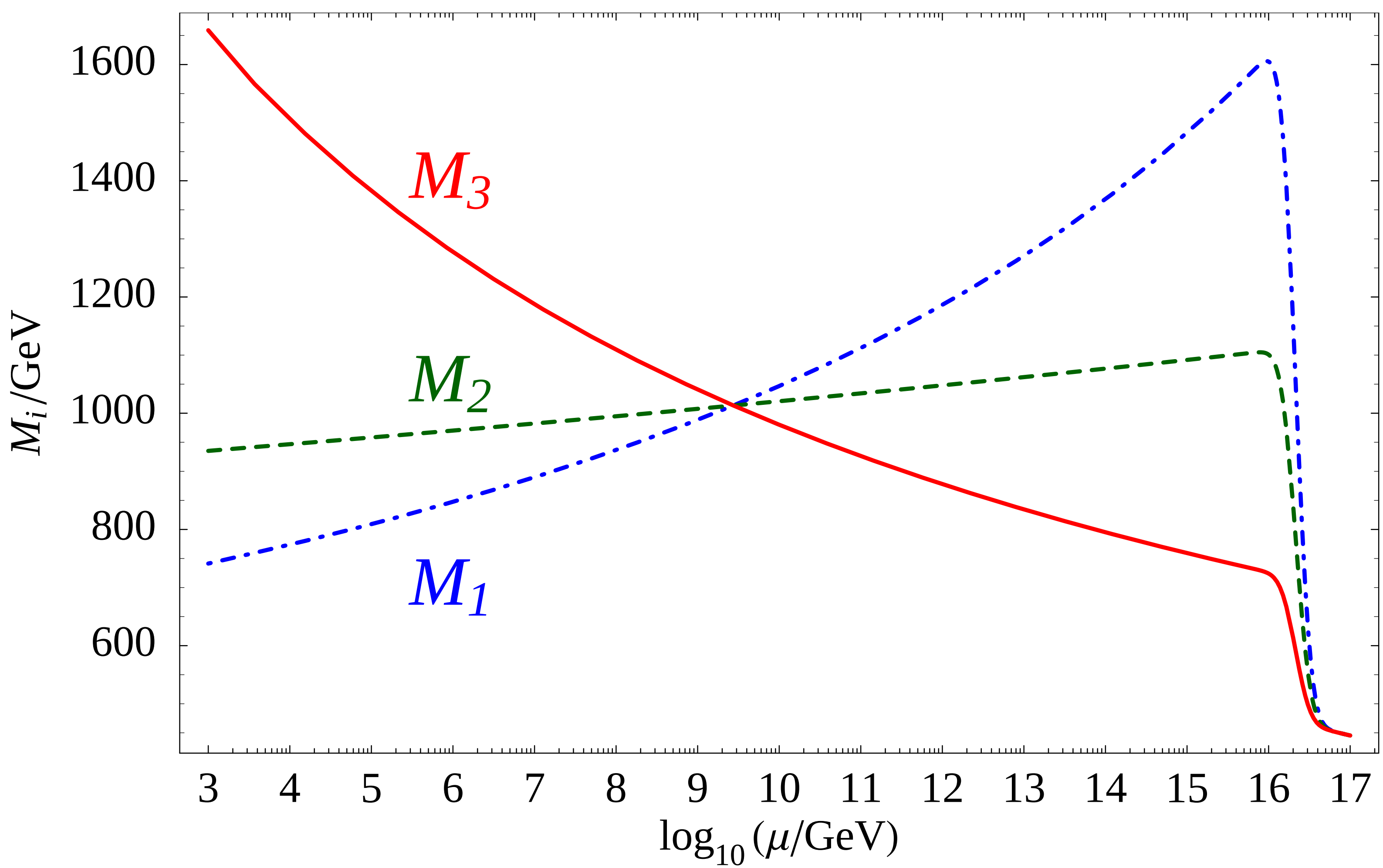
of comparable size.

- M_{anomaly} is proportional to the β function, i.e. negative for the gluino, positive for the bino
- thus M_{anomaly} is non-universal below the GUT scale

Evolution of couplings



The Mirage Scale



The Mirage Scale (II)

The gaugino masses coincide

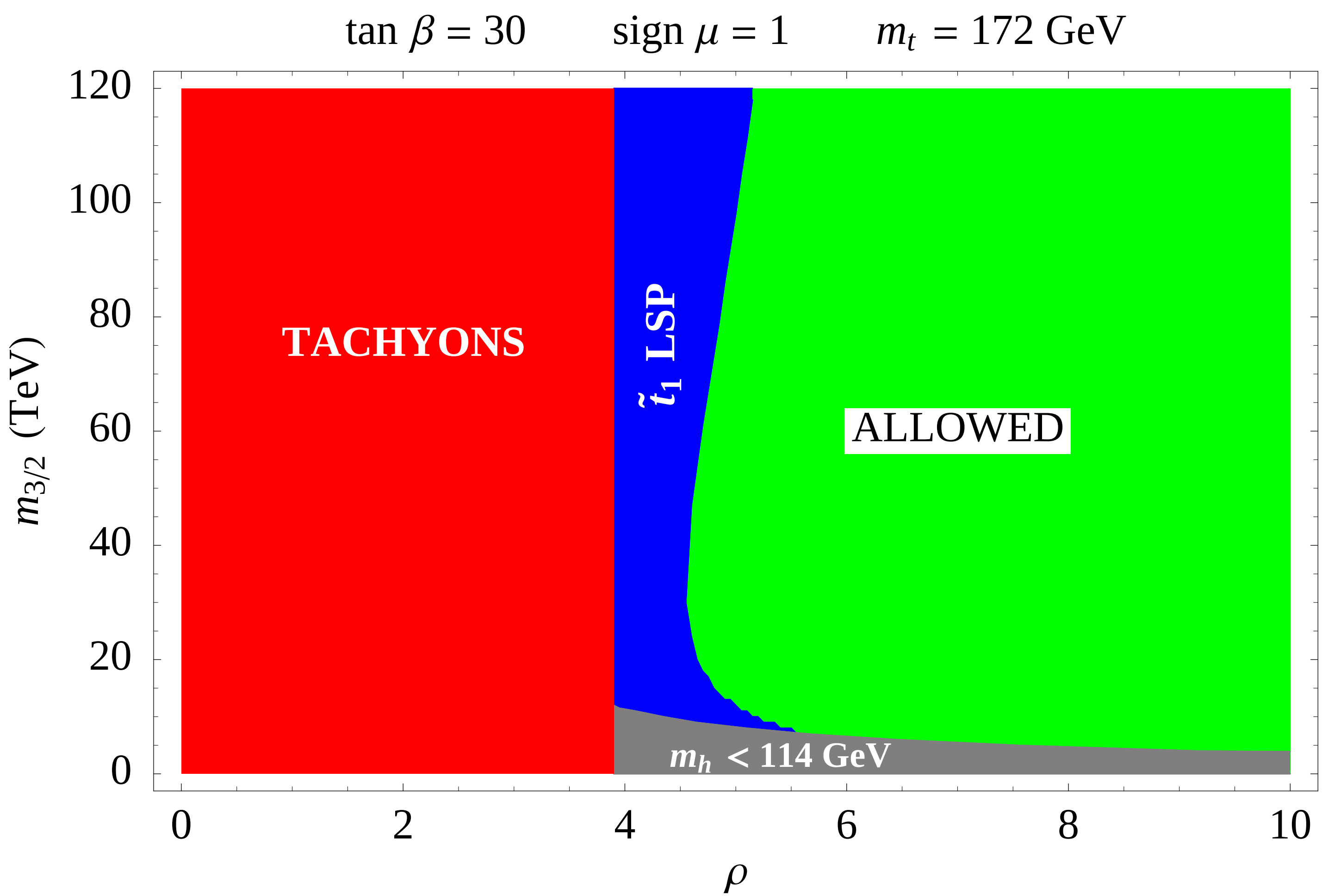
- above the GUT scale
- at the mirage scale $\mu_{\text{mirage}} = M_{\text{GUT}} \exp(-8\pi^2/\rho)$

where ρ denotes the "ratio" of the contribution of modulus vs. anomaly mediation. We write the gaugino masses as

$$M_a = M_s(\rho + b_a g_a^2) = \frac{m_{3/2}}{16\pi^2}(\rho + b_a g_a^2)$$

and $\rho \to 0$ corresponds to pure anomaly mediation.

Constraints on the mixing parameter



(Löwen, HPN, Ratz, 2006)

The “MSSM hierarchy problem”?

The influence of the various soft terms is given by

$$m_Z^2 \simeq -1.8\,\mu^2 + 5.9\,M_3^2 - 0.4\,M_2^2 - 1.2\,m_{H_u}^2 + 0.9\,m_{q_{\mathrm{L}}^{(3)}}^2 + \\ + 0.7\,m_{u_{\mathrm{R}}^{(3)}}^2 - 0.6\,A_t\,M_3 + 0.4\,M_2\,M_3 + \dots\ ,$$

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Mirage mediation improves the situation

- especially for small ρ
- because of a reduced gluino mass and a "compressed" spectrum of supersymmetric partners

(Choi, Jeong, Kobayashi, Okumura, 2005)

- explicit model building required

(Kitano, Nomura, 2005; Lebedev, HPN, Ratz, 2005; Pierce, Thaler, 2006; Dermisek, Kim, 2006)

Explicit schemes I

The different schemes depend on the mechanism of uplifting:

- uplifting with anti-D3 branes (Kachru, Kallosh, Linde, Trivedi, 2003)
  - $\rho \sim 5$ in the original KKLT scenario leading to
  - a mirage scale of approximately 10^{11} GeV

This scheme leads to “pure” mirage mediation:

- gaugino masses and
- scalar masses

both meet at a common mirage scale.

Explicit schemes II

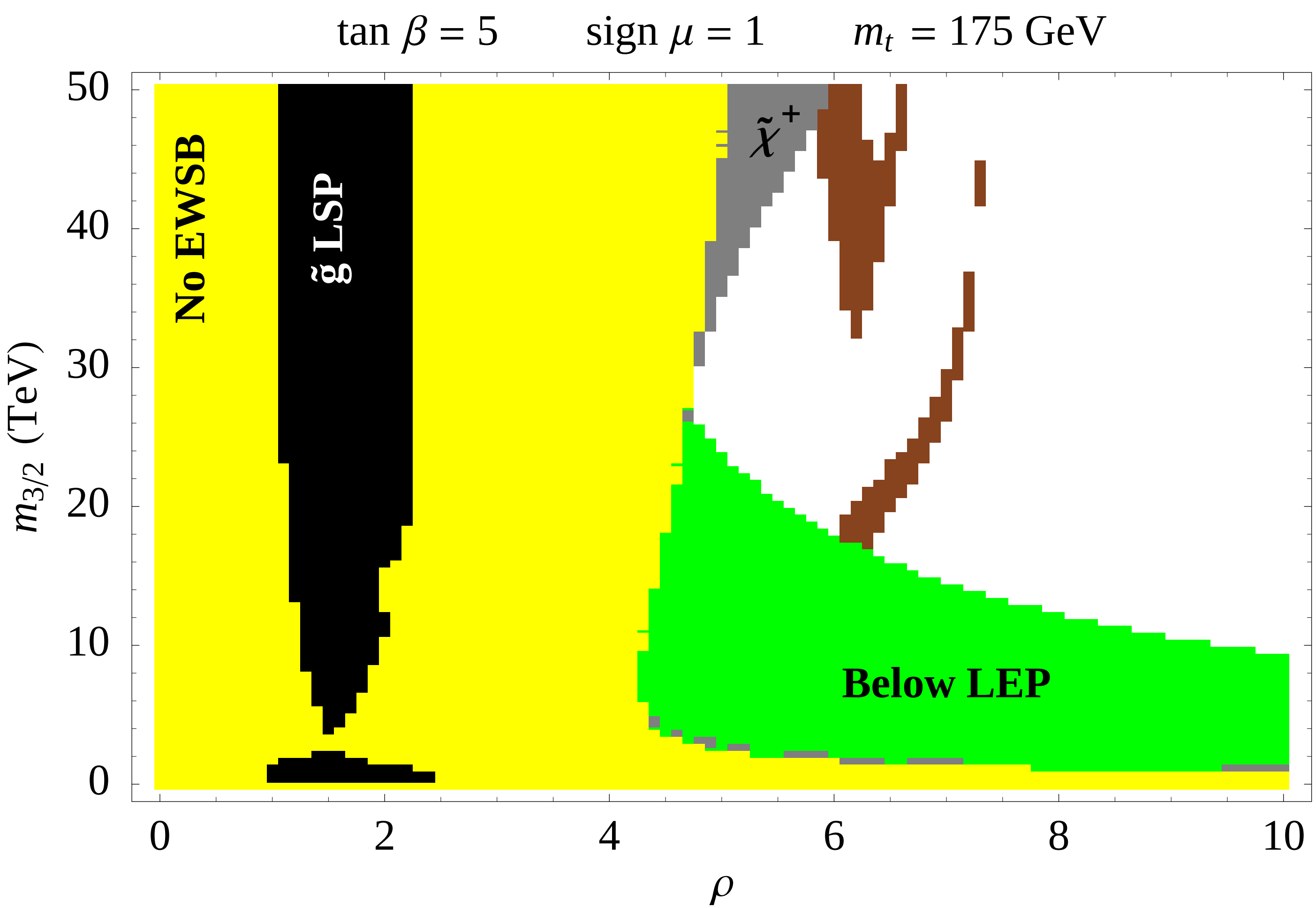
- uplifting via matter superpotentials

  (Lebedev, HPN, Ratz, 2006)

  - allows a continuous variation of ρ
  - leads to potentially new contributions for sfermion masses

- gaugino masses still meet at a mirage scale
- soft scalar masses might be dominated by modulus mediation
- similar constraints on the mixing parameter as in previous scheme

Constraints on the mixing parameter



(V. Löwen, 2007)

Explicit schemes III

- This “relaxed” mirage mediation is rather common for schemes with F-term uplifting
  (Gomez-Reino, Scrucca; Dudas, Papineau, Pokorski; Abe, Higaki, Kobayashi, Omura; Lebedev, Löwen, Mambrini, HPN, Ratz, 2006)
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Main messages

- predictions for gaugino masses are more robust than those for sfermion masses
- mirage pattern for gaugino masses rather generic

The Gaugino Code

How can we test these ideas at the LHC?

Look for pattern of gaugino masses

Let us assume the

- low energy particle content of the MSSM
- measured values of gauge coupling constants

$$g_1^2 : g_2^2 : g_3^2 \simeq \; 1 : 2 : 6$$

The evolution of gauge couplings would then lead to unification at a GUT-scale around 10^{16} GeV

The Gaugino Code

Observe that

- evolution of gaugino masses is tied to evolution of gauge couplings
- for MSSM M_a/g_a^2 does not run (at one loop)

This implies

- robust prediction for gaugino masses
- gaugino mass relations are the key to reveal the underlying scheme

3 CHARACTERISTIC MASS PATTERNS

(Choi, HPN, 2007)

mSUGRA Pattern

Universal gaugino mass at the GUT scale

- mSUGRA pattern:

$$M_1 : M_2 : M_3 \simeq \ 1 : 2 : 6 \simeq \ g_1^2 : g_2^2 : g_3^2$$

as realized in popular schemes such as
gravity-, modulus-, gauge- and gaugino-mediation

This leads to

- LSP χ_1^0 predominantly Bino
- $M_{\mathrm{gluino}}/m_{\chi_1^0} \simeq 6$

as a characteristic signature of these schemes.

Anomaly Pattern

Gaugino masses below the GUT scale determined by the β functions

- anomaly pattern:

$$M_1 : M_2 : M_3 \simeq \ 3.3 : 1 : 9$$

at the TeV scale as the signal of anomaly mediation.

For the gauginos, this implies

- LSP χ_1^0 predominantly Wino
- $M_{\mathrm{gluino}}/m_{\chi_1^0} \simeq 9$

Pure anomaly mediation inconsistent, as sfermion masses are problematic in this scheme (tachyonic sleptons).

Mirage Pattern

Mixed boundary conditions at the GUT scale characterized by the parameter ρ (the ratio of anomaly to modulus mediation).

- $M_1 : M_2 : M_3 \simeq 1 : 1.3 : 2.5$ for $\rho \simeq 5$
- $M_1 : M_2 : M_3 \simeq 1 : 1 : 1$ for $\rho \simeq 2$

The mirage scheme leads to

- LSP χ_1^0 predominantly Bino
- $M_{\rm gluino}/m_{\chi_1^0} < 6$
- a “compressed” gaugino mass pattern.

Conclusion

String theory provides us with new ideas for particle physics model building, leading to concepts such as

- Local Grand Unification
- Mirage Mediation and a compressed SUSY spectrum

Geometry of extra dimensions plays a crucial role:

- localization of fields on branes,
- presence of warped throats

LHC might help us to verify some of these ideas!